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**13. ABSTRACT** *(Maximum 200 words)*

The signing of the CTBT creates the challenge of monitoring the globe to ensure that there is no nuclear weapons testing. This means that the International Monitoring System must detect, locate, and identify with a high degree of accuracy a large number of seismic events. Individual countries will need to evaluate the events and discriminate man-caused events from naturally occurring seismicity. In regions of high seismicity and mining, the task is difficult without regional characterization and evaluation of the transportability of seismic wave discriminants. South America has regions of active seismicity and mining, yet many of these events are not to be found in the global bulletins. Although South America is not currently a region of geopolitical interest, still it remains a region which is not well understood and in which traditional discriminants do not always work. For example, Chile leads the world in copper production. Thus mining activity occurs on a daily basis and Chile is located above an active subduction zone, hence the discimination problem. Shallow earthquake and mine blast data (both for sub-surface and open pit) have been very thoroughly analyzed; the data were recorded on a local network. Amplitude ratio have been applied to test the P/S wave discriminate transportability through Chile.

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Final Report

# BROADBAND SEISMIC RECORDINGS OF MINING EXPLOSIONS AND EARTHQUAKES IN SOUTH AMERICA

AFOSR Contract #94-1-0147

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# Characterization of Mine Blasts and Shallow Earthquakes in Central Chile

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## Introduction

With the signing of the CTBT comes the challenge of monitoring the globe to ensure that there is no nuclear weapons testing. In simple terms, this means that the International Monitoring System (IMS) must detect and locate with high accuracy a large number of seismic events. Individual countries will need to evaluate the events and discriminate man-made from naturally occurring seismicity. In regions of high seismicity and mining, the task is difficult without regional characterization and evaluation of the transportability of discriminants. South America has regions of active seismicity and mining, yet many of these events are not regularly reported in the global bulletins. Although South America is not a region of high concern at the moment, it is an area which was formerly of concern and one where traditional discriminants don't always work. Chile has the largest reserves of copper in the world and leads the world in copper production from both open pit and underground mines (Bernstein, 1990; Lasota, 1992). All this mining activity involves mine blasting on a daily basis. Chile is located above an active subduction zone hence, it is also a region of very high background seismicity (Fig. 1) Mine practices vary worldwide and it can be difficult to distinguish between different types of man-made blasting and earthquakes. We have analyzed shallow earthquake and mine blast data recorded on a local seismic network in central Chile. We have applied P/S amplitude ratio discriminates to determine if this discriminate is transportable to tectonicly active subduction zone environments such as central Chile.

## P/S Amplitude Ratio Discriminants

One of the widely used discriminants is P/S (or P/Lg) amplitude ratios (Blandford, 1995). It has been found that this discriminant has some use at 1 Hz but works best at higher frequencies (Blandford, 1995). Numerous studies have shown that P/S ratio discriminants work well ; Dysart and Pulli (1990) have shown that P/S ratios above about 5 Hz works well in Scandinavia, Baumgardt and Der (1993) showed that it worked well in Europe, Kim et al., (1993) showed that it worked well in New York, and Walter et al.

1994) showed it worked well for earthquakes and explosions at NTS. However, Baumgardt (1994) found that P/S ratio discriminants failed for some mine blasts which fall in the earthquake population. Walter et al. (1994) also found that it failed for some explosions in materials with high dry porosity and extremely shallow earthquakes. Clearly, both P and S waves can be distorted by regional structure and attenuation, hence, the transportability of the P/S ratio as a discriminant is regionally dependent.

Mine blasts are very common in many parts of the world and are particularly numerous in Chile. Mine blasts are often in the magnitude range of 2.5 to 4.0, similar in magnitude to that expected for a decoupled nuclear explosion in the range of 1 to 10 kt (Blandford, 1995). Mine blasts often have complex and variable sources and can produce seismograms which are complex. The distributed nature of mine blasts and the typical geometry of a mine "bench" often produce significant S-wave energy in the seismogram. Although the time delay pattern of ripple fire explosions can sometimes be identified in the spectra, this is not always the case. Many studies have used mine blasts as equivalents to nuclear explosions when looking at P/S discriminants assuming that if a discriminant worked for mine blasts it would work for nuclear explosions. However, this may not be the case and the character of the mining activity needs to be documented in each region

## Data Analysis and Results

### Data

We have analyzed 42 shallow seismic events in central Chile recorded on the University of Chile local seismic network (Fig. 2, Table 1 and 2). The seismic network has short-period, 2 Hz sensors that record at 50 samples per sec. The network has an aperture of approximately 150–200 km and is primarily used for earthquake hazards. We looked at a set of 42 shallow events recorded by this short-period network. The event locations were determined by the local network using the velocity model shown in Table 3. The events havelocal duration magnitudes between 2.5 and 4.0. Figure 3 shows a record section plot of an event (01/04/95, duration magnitude 3.5) that locates at the Disputuda mine. This event also occurred on a Tuesday at 11.32 a.m. local Chile time. Figure 4 shows an earthquake (5/7/96, duration magnitude 3.8) that is located well away from any known mining activity. Both events show a strong P and S arrival out to approximately 140 km. Eight out of the 42 events, locate within a few km of the Disputada mine. These 8 events occur between 11:30 and 7:30 local Chile time and 7 of the events occur on weekdays.

## Disputada Mine and Vicinity

The copper and gold mineralization in Chile are closely linked to the development of the Andean cordillera since late Paleozoic time. The porphyry copper deposits occupy a sinuous belt over 2000 km long and 30 km wide that overlap with parts of the present day active volcanic arc. The porphyry copper deposits are typically hosted by subvolcanic intrusives and range in age from Pliocene in southern Chile to Eocene in northern Chile (Shatwell, 1990). The Disputada mine is part of this belt and is located 50 km northeast of Santiago high in the Andes at an elevation of 3600m.. The Disputada mine is a large open pit porphyry copper mine. The Pliocene age Disputada stock has a mineralized area covering about $12 km^2$ (Bernstein, 1990). The Andina mines Sur-Sur (open pit) and Rio Blanco (underground mine) are on the other side of the mountain at an elevation of nearly 4000m northeast of Disputada and mine the same ore body (Shatwell, 1990).

## Signal/Noise Analysis

We first identified which events and stations had good signal to noise for both the P and S wave to determine which frequency bands were appropriate to use for P/S amplitude ratios. Figure 5 shows a P wave amplitude-frequency plot of signal to noise for an event recorded on 01/04/94 at stations FCH (Dist=21 km), PCH (Dist=58 km), JACH (Dist=58 km), and ROCH (Dist.=70km). The signal and noise window duration is a function of the distance to the station. The signal to noise varied with the station and distance. For example station FCH had good signal to noise from 1 to nearly 25 Hz but ROCH only had good signal to noise between 1 and 6 Hz. Figure 6 shows a similar plot for the S wave for the same event and stations. We found very little if any energy for these events beyond about 15 Hz except at the very closest station.

## P/S Wave Amplitude Ratios

We have determined the P and S wave amplitude in frequency bands of 1-3 Hz, 4-6 Hz, 6-8 Hz, and 9-11 Hz for each of the 42 events if there was good signal to noise in that frequency band. For the smallest events with magnitudes less than 3 we could usually only use the closest few stations. We also had less events with good signal to noise at the 9-11 Hz frequency range. Figure 7 shows a plot of the log(P/S) amplitude ratio as a function of distance for each band width with the events located at the mine plotted as stars and the other events plotted as circles. We then determined the best fit line through all the data for a distance correction and remove it from the data.

After the distance correction we separated the events into mine blasts and earthquakes based primarily on location. We then determined the best fit line to each population (Fig. 8). We find that at 1-3 Hz there is no difference between the two populations but at higher frequencies, the mine blasts have a higher average P/S amplitude ratio than the earthquakes (Fig. 8). However, there is a large amount of overlap in the P/S ratios of mine blasts and earthquakes. This overlap makes using the P/S ratio as a discriminant for a single suspect event very difficult in this region.

## Spectrograms

We have also calculated spectrograms for each event at several of the closest stations to look for spectral scalloping that is often indicative of ripple fire blasting and other characteristics that might help distinguish the mine blasts from the earthquakes. We use a frequency window of 0 to 15 Hz, a 1.5 sec time slice, and a 1 sec sliding window to calculate the spectrograms. We used a total time duration that includes both the P and S wave. We focused on spectrograms calculated for stations FCH and PCH. These are the two closest stations to the mines and have the best recorded signals.

Figure 9a-d show spectrograms for events that locate at the mine for stations FCH (Dist.=23 km) and PCH (Dist.=58 km). In this case the azimuth and distance to each stations is similar because the events have similar locations. A qualitative assessment of spectrograms from station PCH suggests these events are mine blasts with strong P wave energy relative to S. However, at station FCH the spectrograms show relatively low amplitude P wave energy relative to S which is more characteristic of earthquakes.

Figure 10a-d show earthquakes (events that do not locate near a mine) located east of stations FCH (Dist.=23-32 km) and PCH (Dist.=30-47 km). The azimuths and distances vary because the events have different locations (Fig. 2). We chose events as close to the mines as possible with similar distances to stations FCH and PCH for comparison. However, it is clear that the propagation paths are different. These shallow earthquakes have spectrograms at station FCH that have characteristics of earthquakes. But the spectrograms from station PCH show very large amplitude P relative to S. Station PCH has well recorded P-waves with frequencies above 10 Hz for several of these events. It is possible that this station site has high S-wave attenuation so that S wave amplitudes are diminished. This would greatly affect the P/S amplitude ratios used in discrimination studies. However, station FCH does not show large variations between the events occurring at the mine and earthquakes. Hence, without more site characterization it is difficult to distinguish between shallow earthquakes and mine blasts in this environment.

The event on 10/20/94 is a "suspect" event in the sense that it locates near the mine (about 18 km east of the Disputada mine, see Fig. 2) but has a depth of 12 km from the local network. The event is small (duration magnitude = 3.27) and not well recorded across the network, hence, the errors in location (including depth) are probably large (Fig. 11). In order to determine if this event is an earthquake or a mislocated mine blast we inspected the spectrogram for a 10 sec window including both the P and S wave for frequencies between 1 and 15 Hz (Fig. 12). The P and S wave amplitudes are similar for stations PCH but the S wave amplitude is much larger than the P wave for station FCH. The event occurred at 3:46 in the afternoon on a weekday compatible with blasting practices. However, it is still difficult to confirm if it is a mislocated mine blast or an earthquake.

## Conclusions and Discussion

The mining activity in Chile provides an excellent test bed for the transportability of spectral discriminants. Mining activity provides a challenge for monitoring a CTBT. In Chile, there are explosions weekly that have local magnitudes in excess of 3.0. In this study we have found little spectral scalloping, which has been reported in studies of mining activity in the U.S. (i.e., Kim et al., 1992). Further, the P/S amplitude ratios for mine explosions and earthquakes are similar; at mid-periods (1–3 Hz) the ratios are nearly identical, but higher frequencies, the mine explosions have a higher P/S ratio, but there is large scatter and significant overlap of the populations. Further, we find large variations in P/S amplitude ratios for the same event at different stations. This is consistent with previous work on NPR (Tinker and Wallace, 1997), which showed that site and propagation effects are extremely important and require empirical calibration.

The results of this study imply that historical catalogues of waveforms are important for confidence building in a CTBT environment. It is apparent that transportability of discriminants is difficult, especially to an “extreme” geologic environment such as the Andes. Therefore, events which may be deemed suspicious in the future will require some mechanism for quantitative assessment. Many areas of the world have local or regional seismic networks. These networks vary in sophistication but provide a reference baseline.

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Table 1. List of events used in this study.

| EVENT # | EVENT ID | GMT | SANTIAGO TIME | CONVERT TIME | EVENT LAT | EVENT LONG | DEPTH | MAG |
|---|---|---|---|---|---|---|---|---|
| 1 | 940104 | 14:32:40.51 | 11:32:40.51 | 11.55 | 33.14 | 70.29 | 6.82 | 3.51 |
| 2 | 940516 | 21:38:34.76 | 17:38:34.76 | 17.65 | 33.15 | 70.31 | 5.12 | 3.51 |
| 3 | 940517 | 19:30:30.84 | 15:31:00.00 | 15.52 | 33.14 | 70.29 | 7.07 | 3.61 |
| 4 | 940925 | 20:14:26.75 | 16:14:00.00 | 16.23 | 33.14 | 70.30 | 5.34 | 3.48 |
| 5 | 940926 | 17:02:48.03 | 13:03:00.00 | 13.05 | 33.13 | 70.30 | 9.17 | 3.66 |
| 6 | 941005 | 20:31:11.83 | 16:31:00.00 | 16.52 | 33.16 | 70.31 | 0.00 | 3.63 |
| 7 | 941013 | 22:31:20.08 | 19:31:00.00 | 19.52 | 33.14 | 70.32 | 4.16 | 3.58 |
| 8 | 941020 | 18:45:41.59 | 15:46:00.00 | 15.77 | 33.13 | 70.14 | 11.99 | 3.27 |
| 9 | 950613 | 04:52:00.00 | 00:52:00.00 | 0.87 | 33.73 | 70.38 | 13.00 | 3.44 |
| 10 | 960101 | 21:33:45.24 | 18:34:00.00 | 18.57 | 33.85 | 70.20 | 12.99 | 0.00 |
| 11 | 960107 | 01:46:58.35 | 22:47:00.00 | 22.78 | 33.98 | 70.15 | 8.27 | 2.87 |
| 12 | 960109 | 17:34:35.42 | 14:34:00.00 | 14.57 | 33.61 | 70.05 | 8.43 | 0.00 |
| 13 | 960111 | 02:20:47.25 | 23:21:00.00 | 23.35 | 34.27 | 70.11 | 6.64 | 3.84 |
| 14 | 960119 | 21:33:45.24 | 00:43:00.00 | 0.72 | 33.40 | 70.14 | 11.65 | 3.95 |
| 15 | 960125 | 01:46:58.35 | 01:39:00.00 | 1.65 | 34.09 | 70.15 | 8.97 | 2.87 |
| 16 | 960209 | 17:34:35.42 | 03:31:00.00 | 3.52 | 33.63 | 70.04 | 7.83 | 2.62 |
| 17 | 960224 | 23:36:01.79 | 20:36:00.00 | 20.6 | 34.18 | 70.09 | 6.60 | 3.14 |
| 18 | 960228 | 12:58:11.27 | 09:58:00.00 | 9.97 | 33.63 | 70.09 | 6.64 | 0.00 |
| 19 | 960309 | 17:03:36.55 | 14:04:00.00 | 14.07 | 34.01 | 70.13 | 7.01 | 0.00 |
| 20 | 960318 | 22:58:29.29 | 18:58:00.00 | 18.97 | 33.53 | 70.04 | 10.10 | 3.27 |
| 21 | 960321 | 15:33:35.81 | 11:34:00.00 | 11.57 | 34.40 | 70.17 | 5.60 | 2.24 |
| 22 | 960321 | 19:37:00.32 | 15:37:00.00 | 15.62 | 33.69 | 70.00 | 16.02 | 3.21 |
| 23 | 960321 | 19:47:25.62 | 15:47:00.00 | 15.78 | 34.40 | 70.13 | 10.91 | 2.97 |
| 24 | 960322 | 16:26:06.41 | 12:26:00.00 | 12.43 | 33.74 | 70.29 | 15.15 | 2.76 |
| 25 | 960325 | 12:24:00.00 | 08:24:00.00 | 8.4 | 34.01 | 70.13 | 8.33 | 3.14 |
| 26 | 960326 | 11:46:00.00 | 07:46:00.00 | 7.77 | 34.39 | 70.16 | 11.31 | 0.00 |
| 27 | 960409 | 21:42:38.66 | 17:43:00.00 | 17.72 | 34.04 | 70.12 | 8.03 | 0.00 |
| 28 | 960417 | 18:26:20.57 | 14:26:00.00 | 14.43 | 33.91 | 70.04 | 4.50 | 3.75 |
| 29 | 960421 | 01:07:45.79 | 21:08:00.00 | 21.13 | 33.46 | 70.09 | 10.60 | 3.33 |
| 30 | 960424 | 05:47:19.54 | 01:47:00.00 | 1.78 | 34.05 | 70.15 | 8.51 | 3.21 |
| 31 | 960426 | 11:15:59.54 | 07:16:00.00 | 7.27 | 34.00 | 70.16 | 7.66 | 2.97 |
| 32 | 960429 | 05:17:40.50 | 01:18:00.00 | 1.3 | 33.57 | 70.12 | 8.32 | 2.87 |
| 33 | 960430 | 01:02:54.16 | 21:03:00.00 | 21.05 | 33.59 | 70.03 | 9.18 | 3.06 |
| 34 | 960501 | 08:49:34.46 | 04:50:00.00 | 4.83 | 33.55 | 70.23 | 9.90 | 2.87 |
| 35 | 960506 | 19:16:51.56 | 15:17:00.00 | 15.28 | 33.60 | 70.12 | 10.21 | 4.00 |
| 36 | 960507 | 07:26:54.54 | 03:26:00.00 | 3.43 | 33.59 | 70.04 | 10.07 | 3.84 |
| 37 | 960507 | 14:27:08.28 | 10:27:00.00 | 10.45 | 33.56 | 70.03 | 14.32 | 0.00 |
| 38 | 960512 | 01:35:34.95 | 22:36:00.00 | 22.6 | 33.98 | 70.15 | 7.85 | 4.24 |
| 39 | 960613 | 11:45:50.39 | 07:46:00.00 | 7.77 | 33.51 | 70.06 | 8.79 | 3.14 |
| 40 | 960623 | 23:43:08.36 | 19:43:00.00 | 19.72 | 33.95 | 70.14 | 0.49 | 0.00 |
| 41 | 960702 | 21:46:34.41 | 17:47:00.00 | 17.78 | 34.12 | 70.09 | 6.94 | 0.00 |
| 42 | 960705 | 00:47:22.33 | 20:47:00.00 | 20.78 | 34.08 | 70.11 | 7.49 | 3.84 |

Table 2. List of seismological stations in Central Chile

| Station Name | Latitude °S | Longitude °W | Altitude (m) |
|---|---|---|---|
| CACH | 34.143 | 70.572 | 1760 |
| CHCH | 33.933 | 70.653 | 680 |
| CICH | 34.251 | 70.451 | ------ |
| COLN | 34.067 | 70.457 | ------ |
| FCH | 33.328 | 70.291 | 2770 |
| JACH | 32.682 | 70.593 | 1075 |
| LCCH | 33.475 | 71.57 | 180 |
| LNV | 33.956 | 71.411 | 160 |
| PCH | 33.621 | 70.514 | 1010 |
| PEL | 33.144 | 70.685 | 690 |
| ROCH | 32.972 | 71.011 | 2000 |
| SAN | 33.453 | 70.662 | 533 |
| SFDO | 34.614 | 71.014 | 690 |
| TACH | 33.653 | 70.938 | 440 |

Table 3. Velocity model for the Cordilleran region in Central Chile (Acevedo, 1985)

| P Velocity [km/s] | Depth [km] |
|---|---|
| 5.56 | 0.00 |
| 5.97 | 7.65 |
| 6.50 | 16.90 |
| 7.05 | 26.05 |
| 8.00 | 41.50 |

# PDE Events 1994-1995

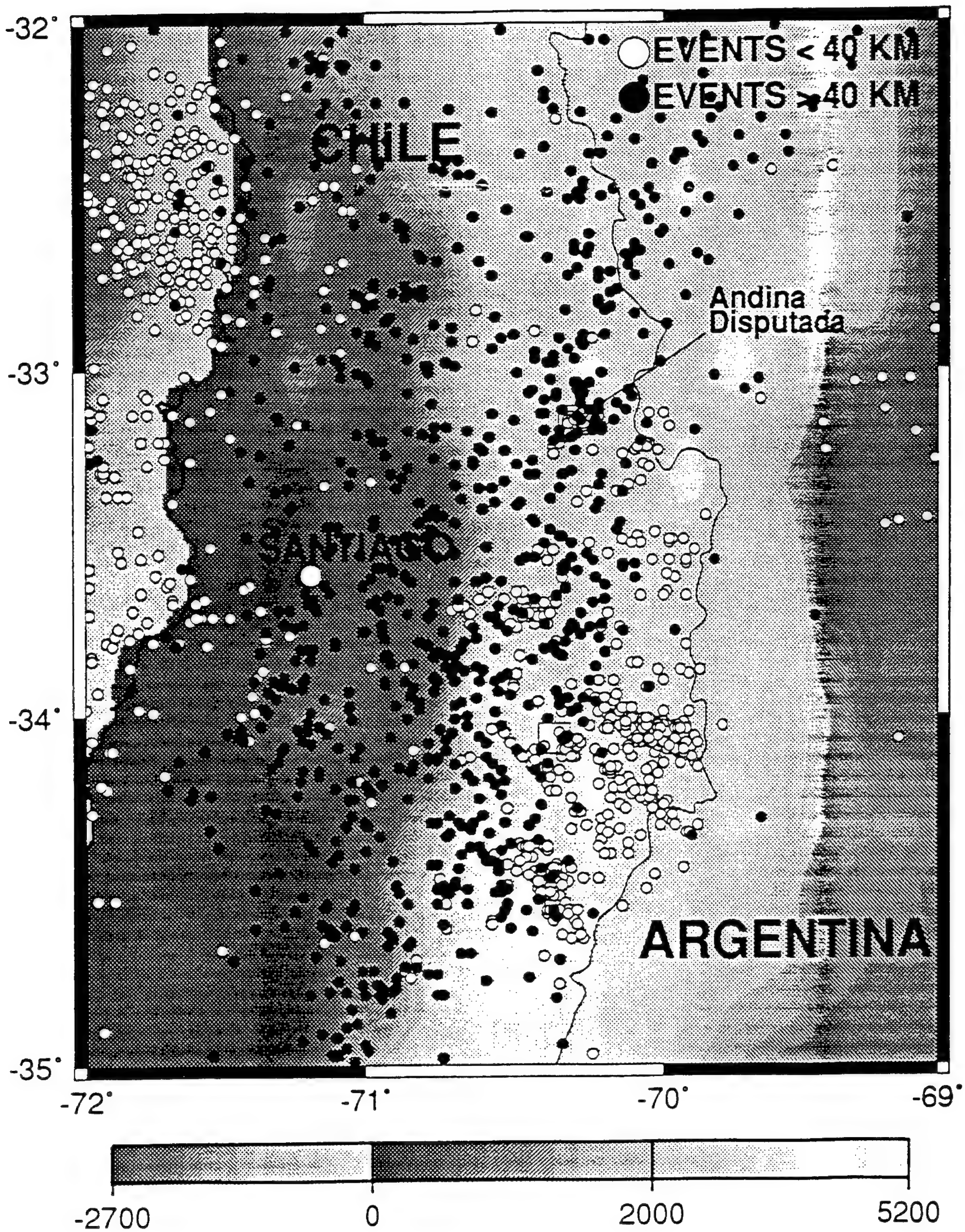



Figure 1. Map of central Chile showing seismicity from the PDE catalogue for a two year period (1994 and 1995). The white circles are events with depths less than 40 km and the black circles are events with depths greater than 40 km. Note that much of the shallow crustal seismicity in Chile is in the high elevations of the Andes in the same region as the large mines.

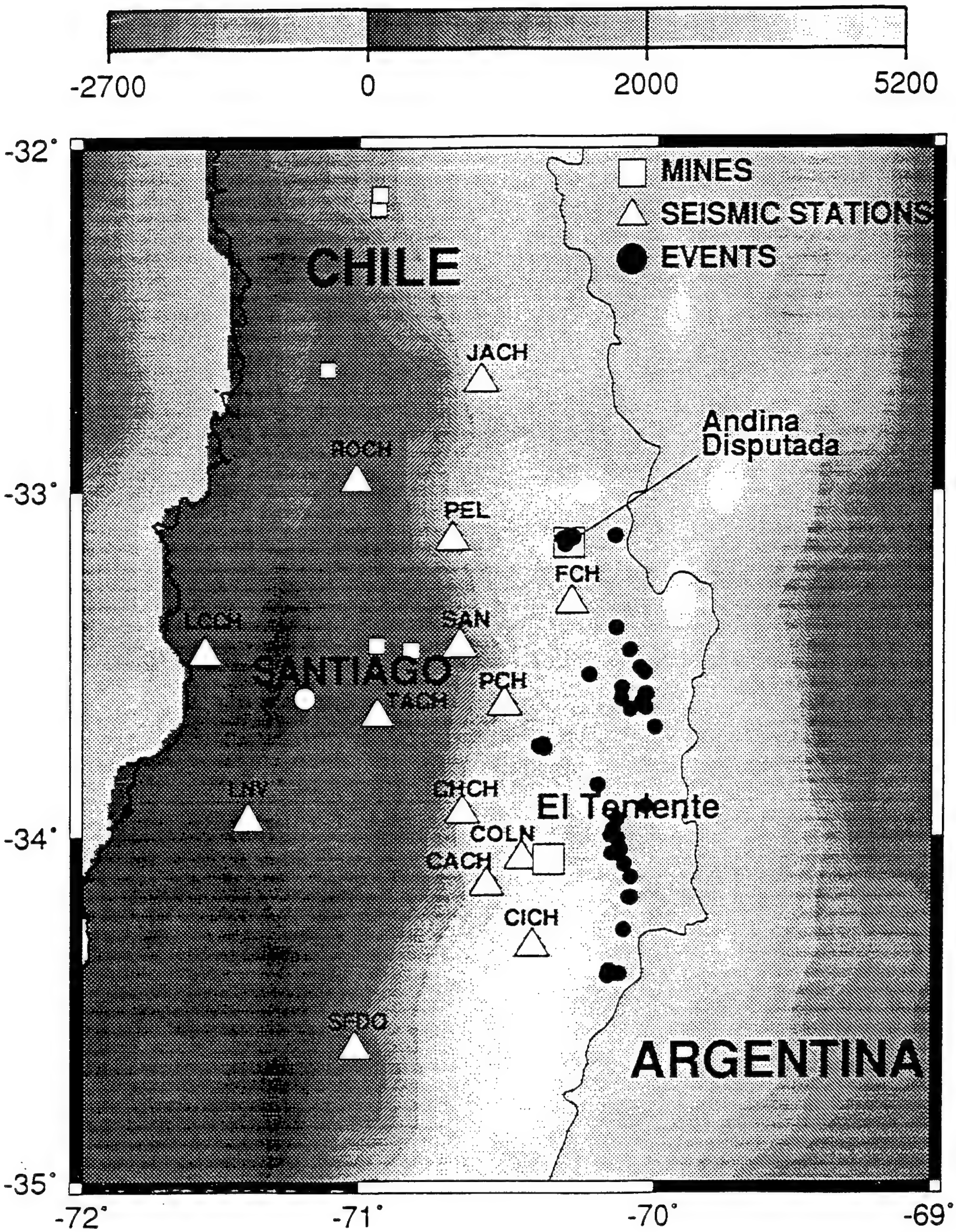



Figure 2. Map of central Chile showing the locations of the short-period seismic network operated by the University of Chile in Santiago, the largest active mines, and the 42 shallow events that we have used in this study.

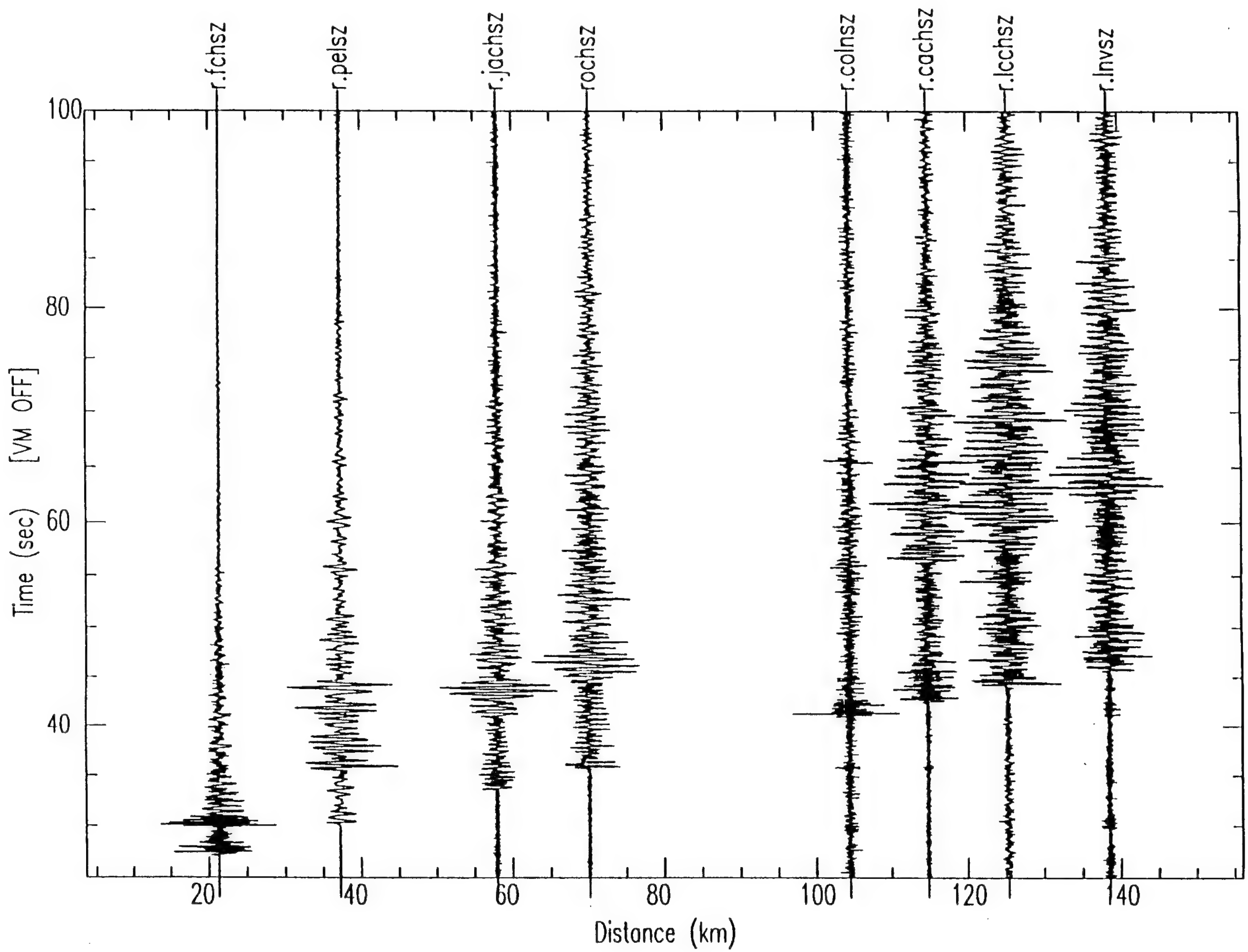



Figure 3. Record section plot of an event on 01/04/94 that is located at the Disputada mine site.

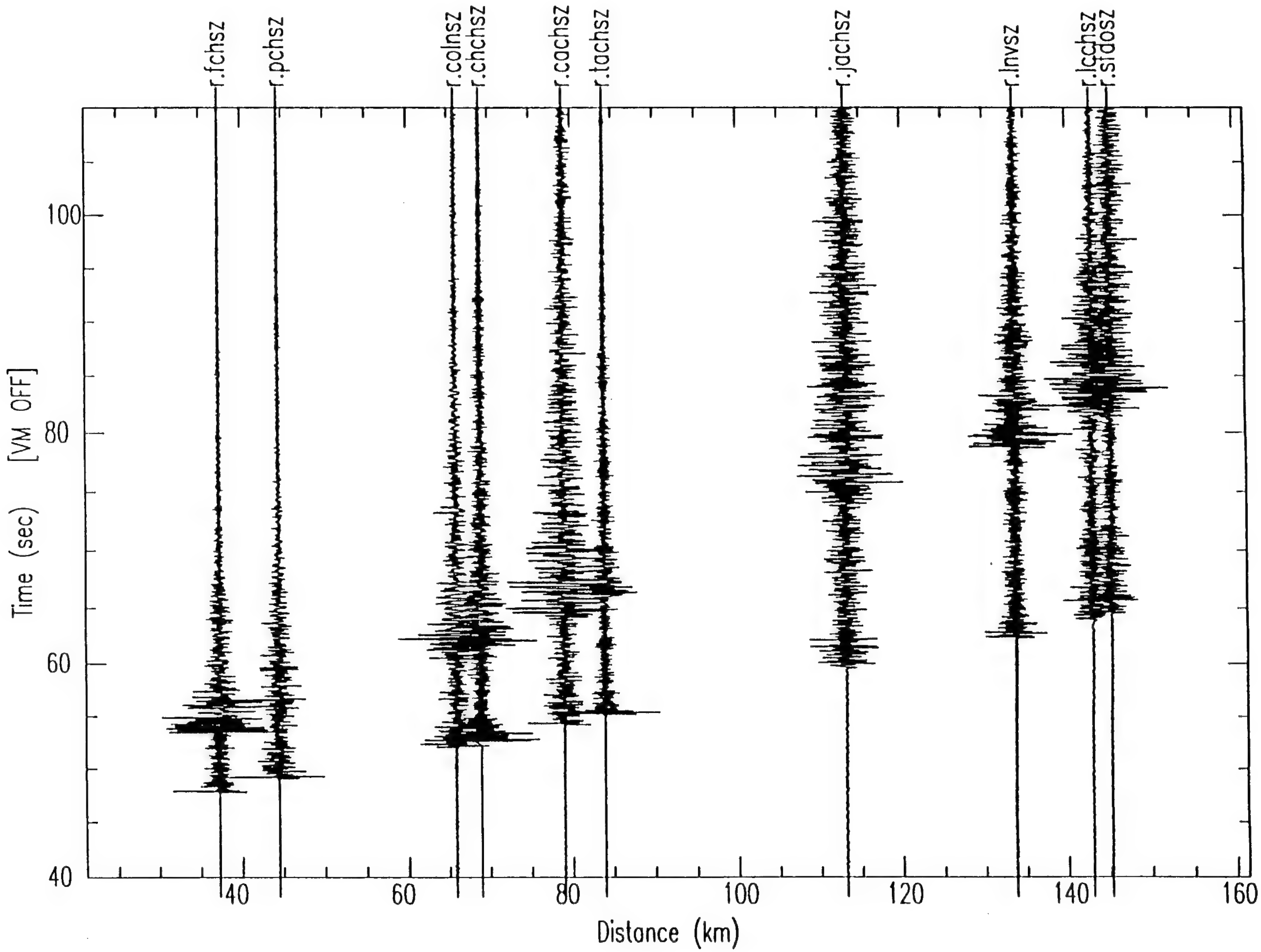



Figure 4. Record section plot of an earthquake on 5/7/96 that is located away from any known mining activity.

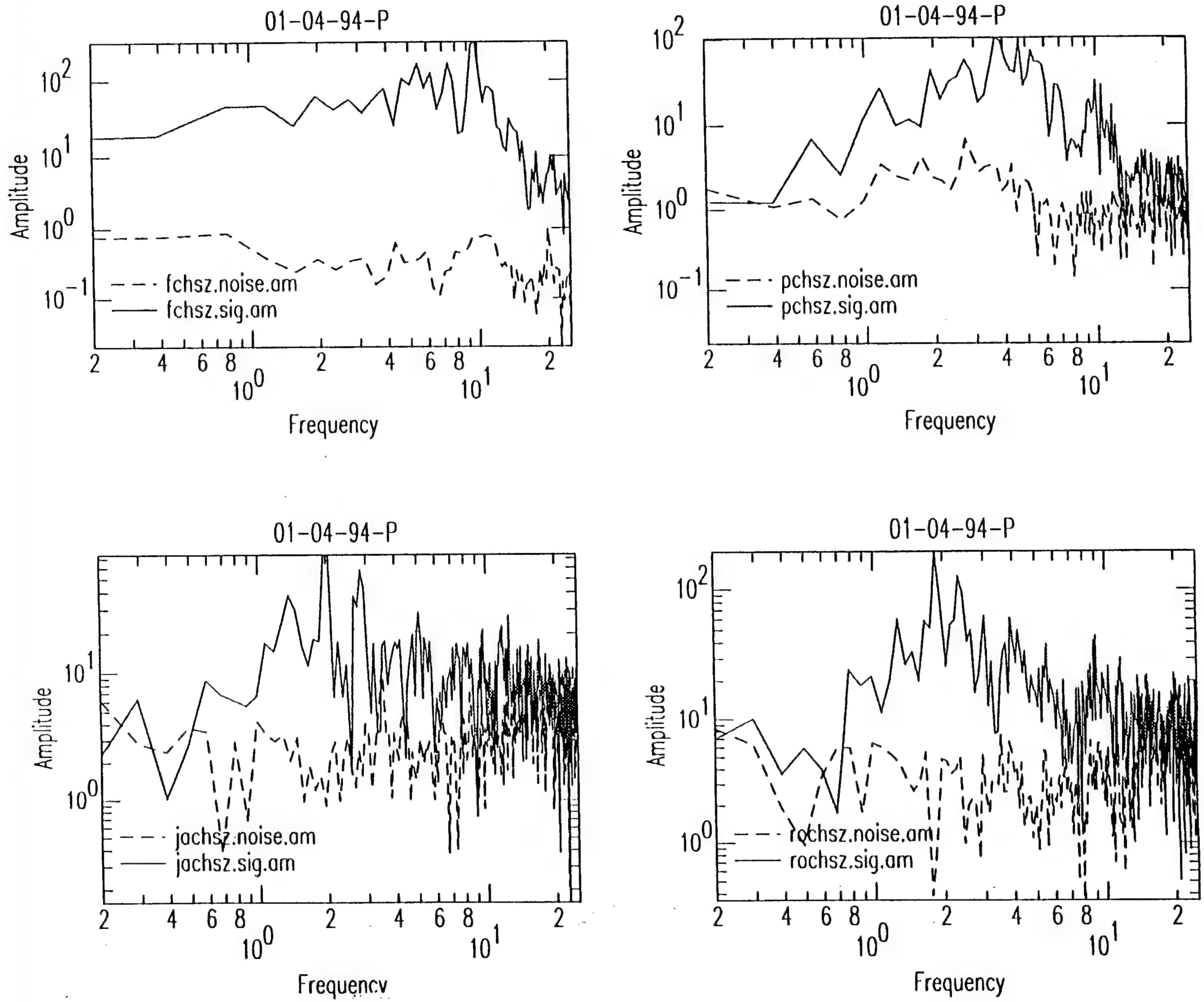



Figure 5. Amplitude - frequency plot of the P wave signal (solid line) to noise (dashed line) for an event recorded on 01/04/94 at stations FCH (Dist.=21 km), PCH (Dist.=58 km), JACH (Dist.=58 km), and ROCH (Dist.=70km).

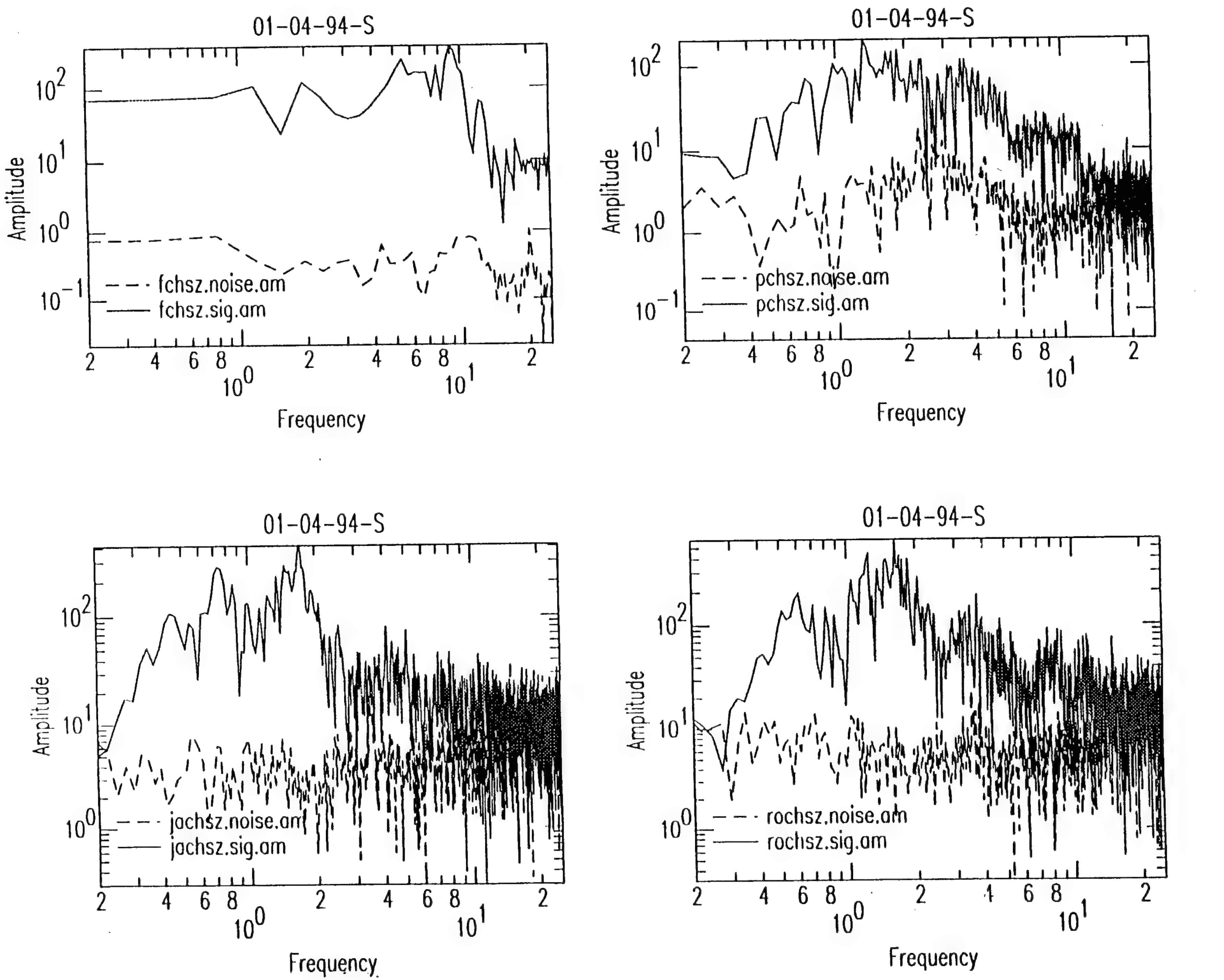



Figure 6. Amplitude - frequency plot of the S wave signal (solid line) to noise (dashed line) for an event recorded on 01/04/94 at stations FCH (Dist.=21 km), PCH (Dist.=58 km), JACH (Dist.=58 km), and ROCH (Dist.=70km).

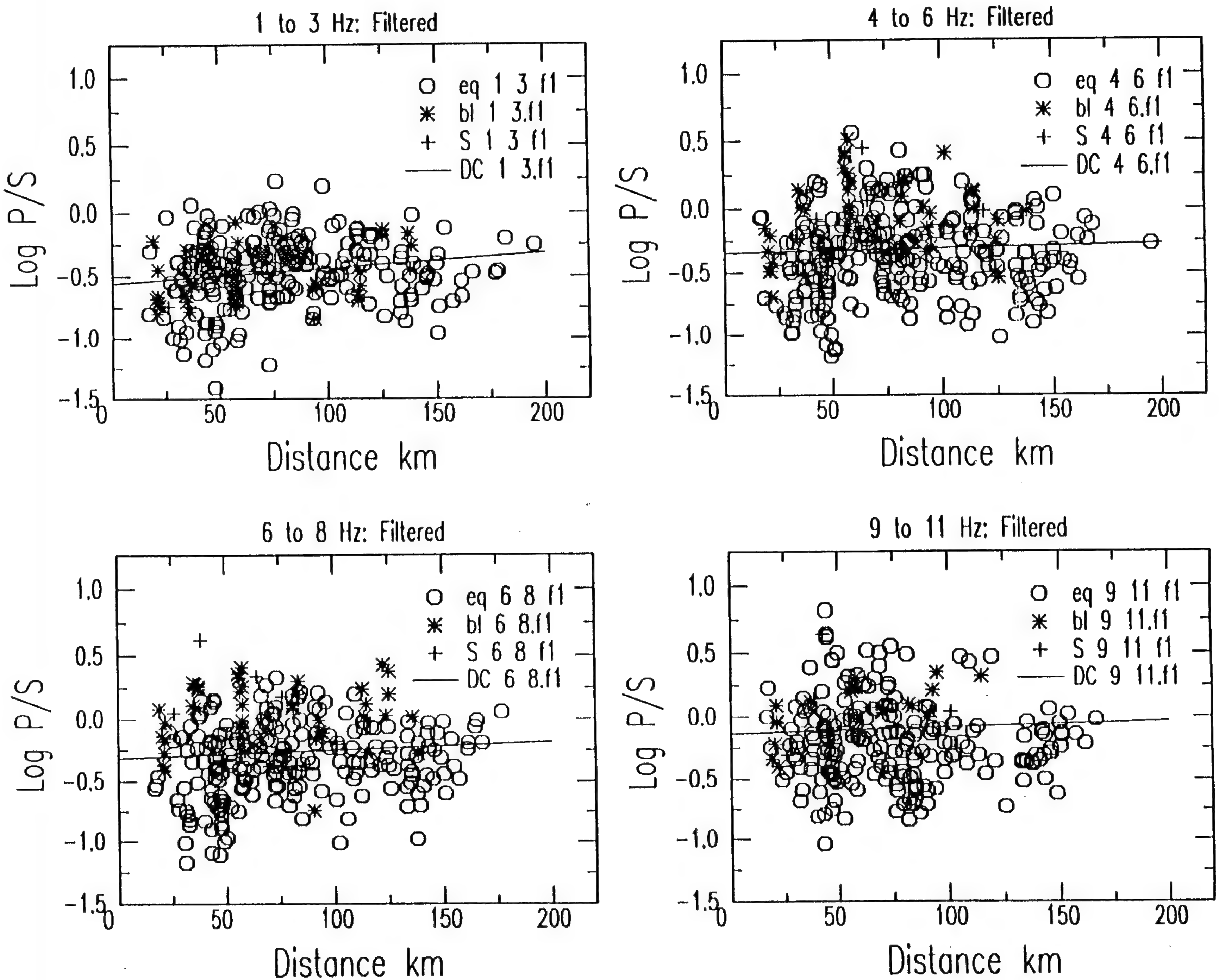



Figure 7. Plot of Log P/S amplitudes for passbands of 1 to 3 Hz, 4 to 6 Hz, 6 to 8 Hz and 9 to 11 Hz as a function of distance for suspected earthquakes (circles) and mine blasts (stars). The best fit line through the data for each passband is shown and removed as a distance correction for Figure 8.

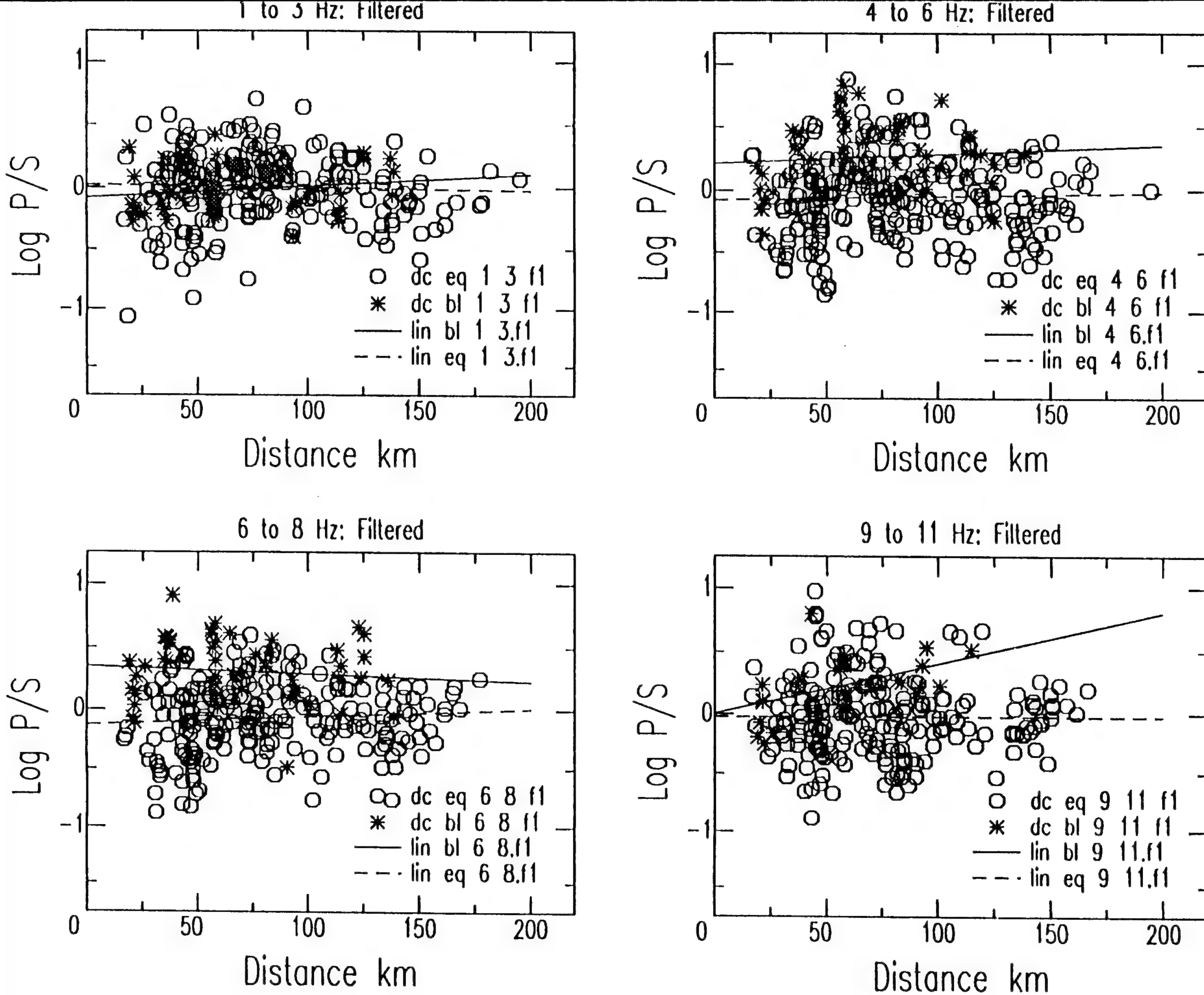



Figure 8. Plot of distance-corrected Log P/S amplitudes for suspected earthquakes (circles), mine blasts (stars) and suspect events (crosses). The best fit line for the earthquakes and mine blasts are shown as dashed and solid lines respectively. Note that for a passband of 1 to 3 Hz there is no difference in the two populations. For higher frequencies the mine blasts have on average a higher P/S ratios than earthquakes but with considerable overlap between the two populations.

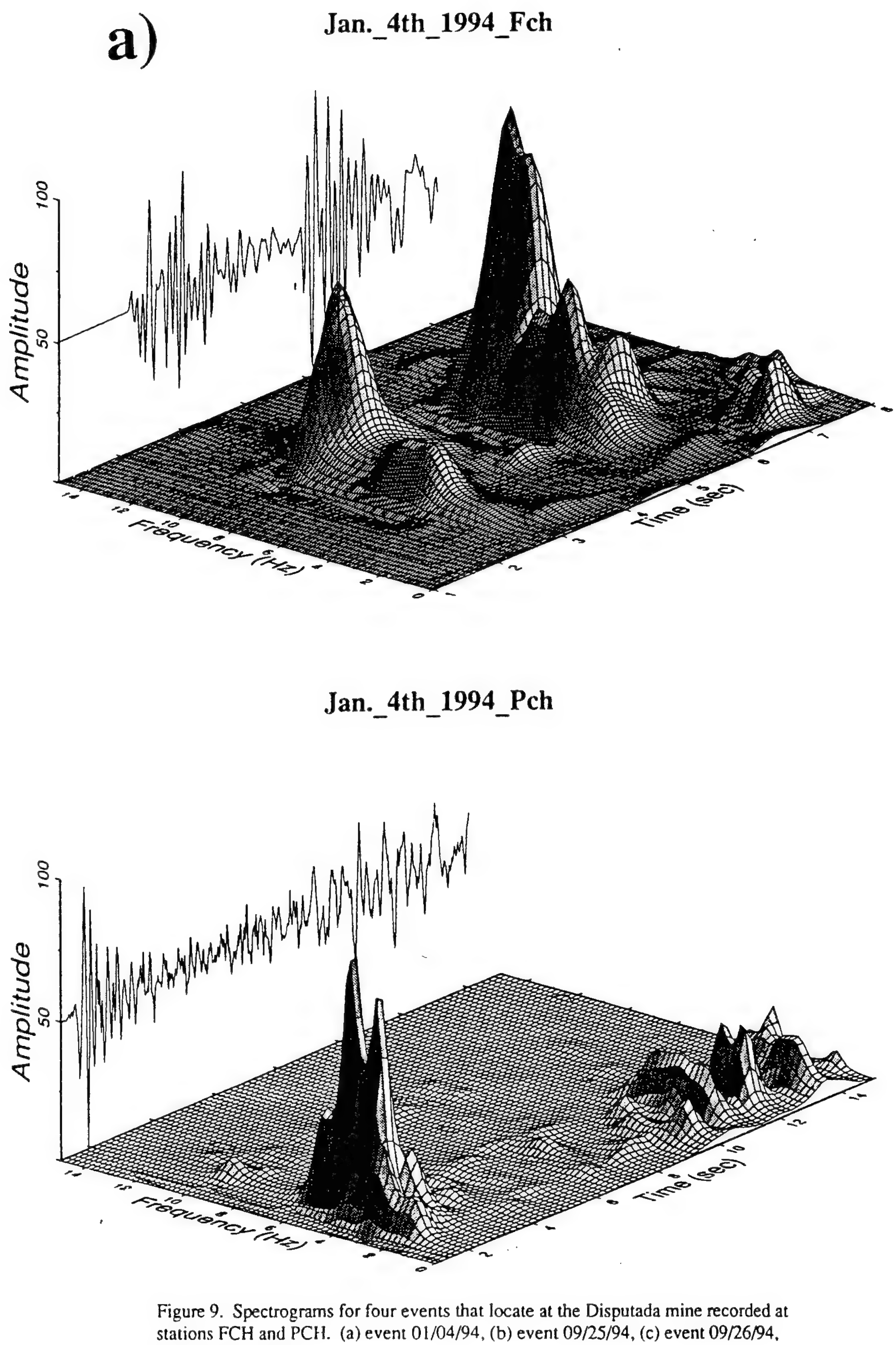
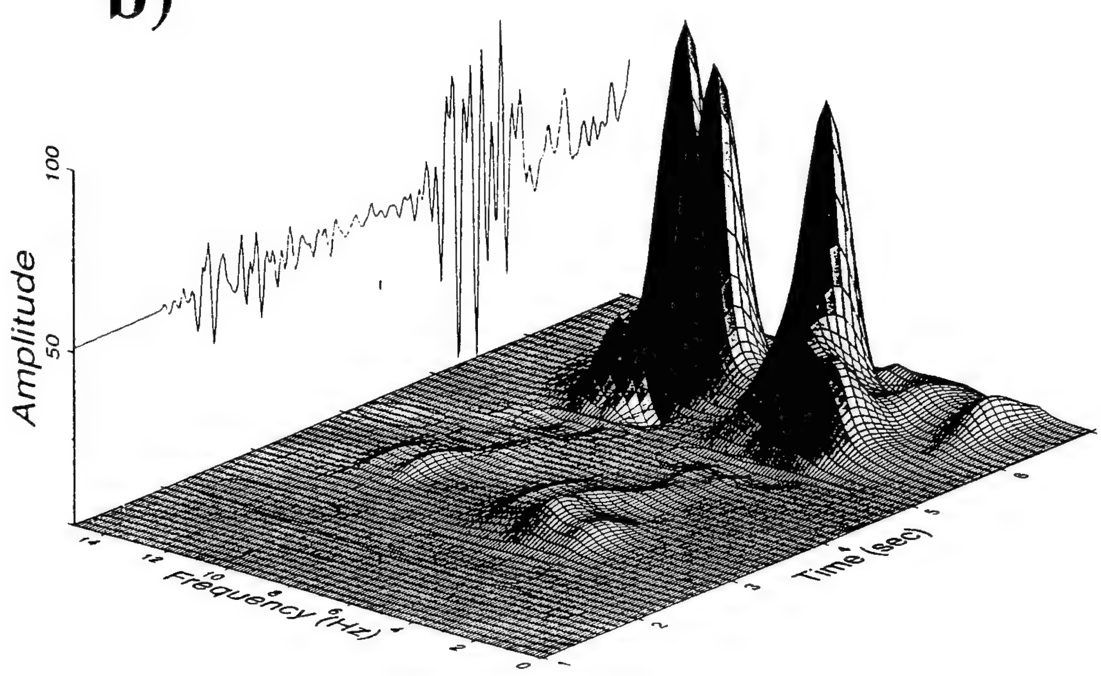


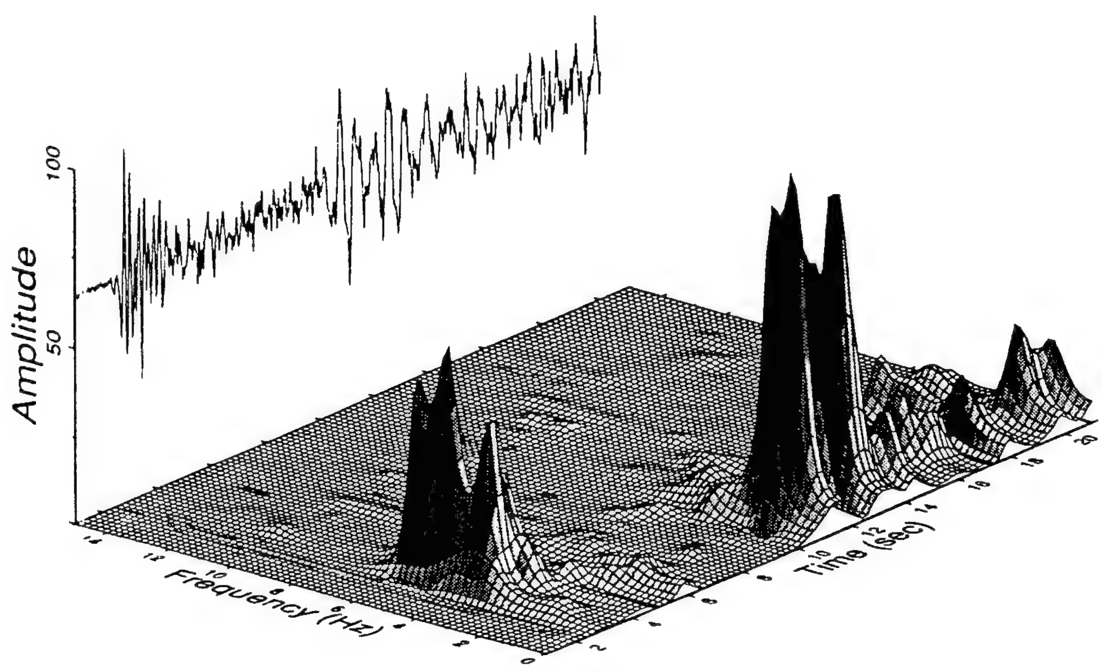

Figure 9. Spectrograms for four events that locate at the Disputada mine recorded at stations FCH and PCH. (a) event 01/04/94, (b) event 09/25/94, (c) event 09/26/94, (d) event 10/13/94.

**b)**

**Sept._25_1994_Fch**

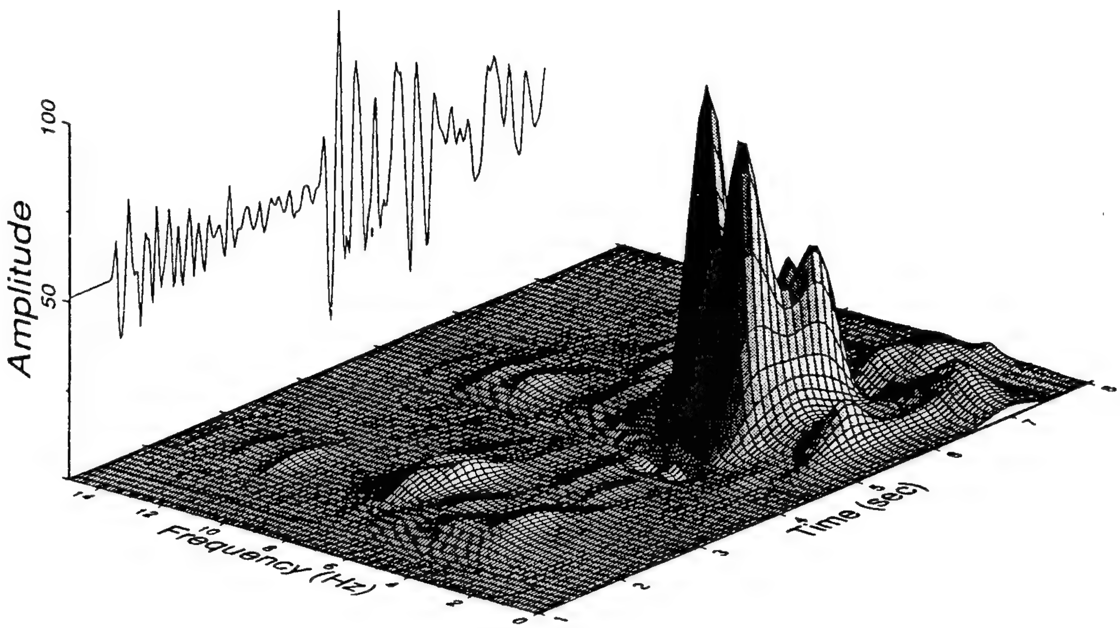



**Sept._25_1994_Pch**

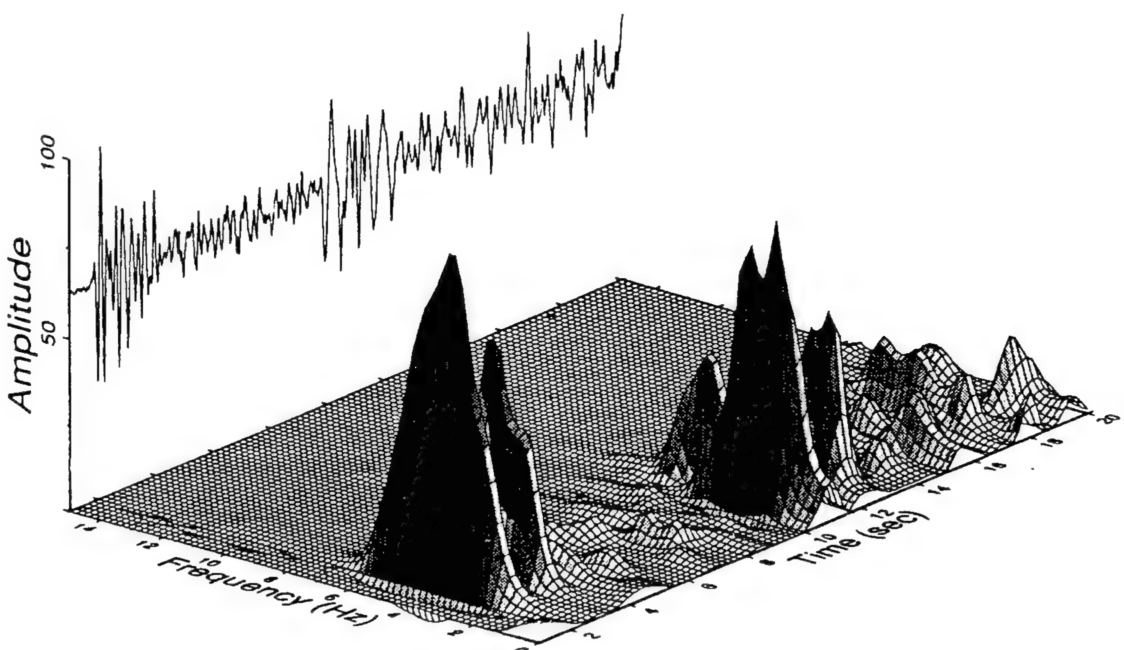


c)

Sept._26th_1994_Fch

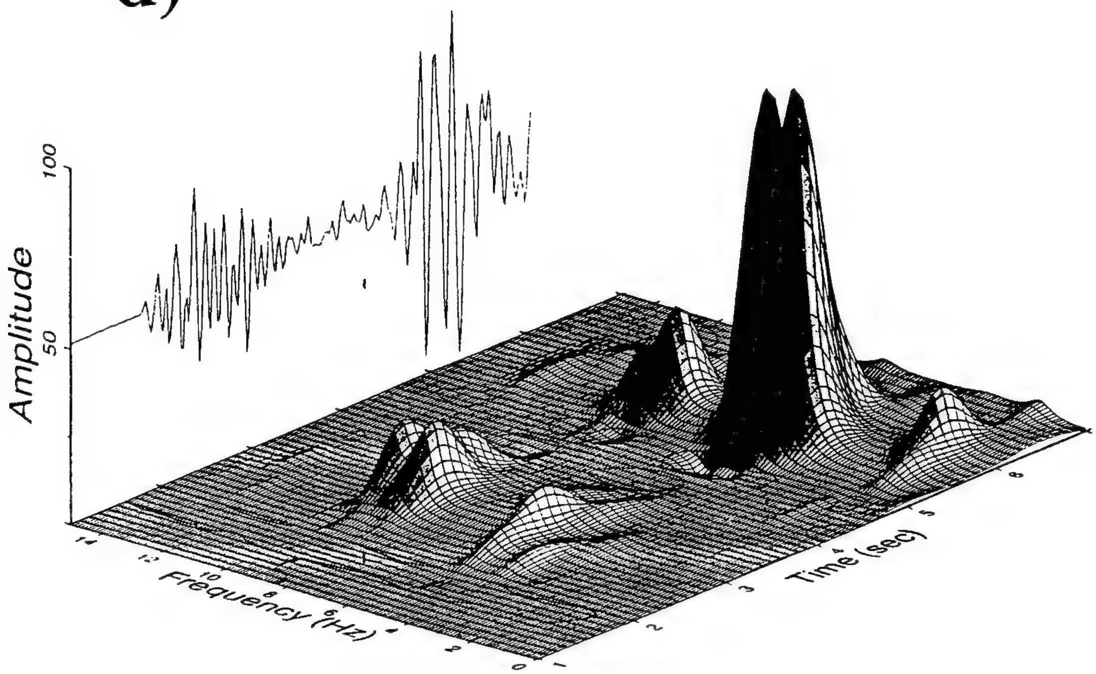



Sept._26th_1994_Pch

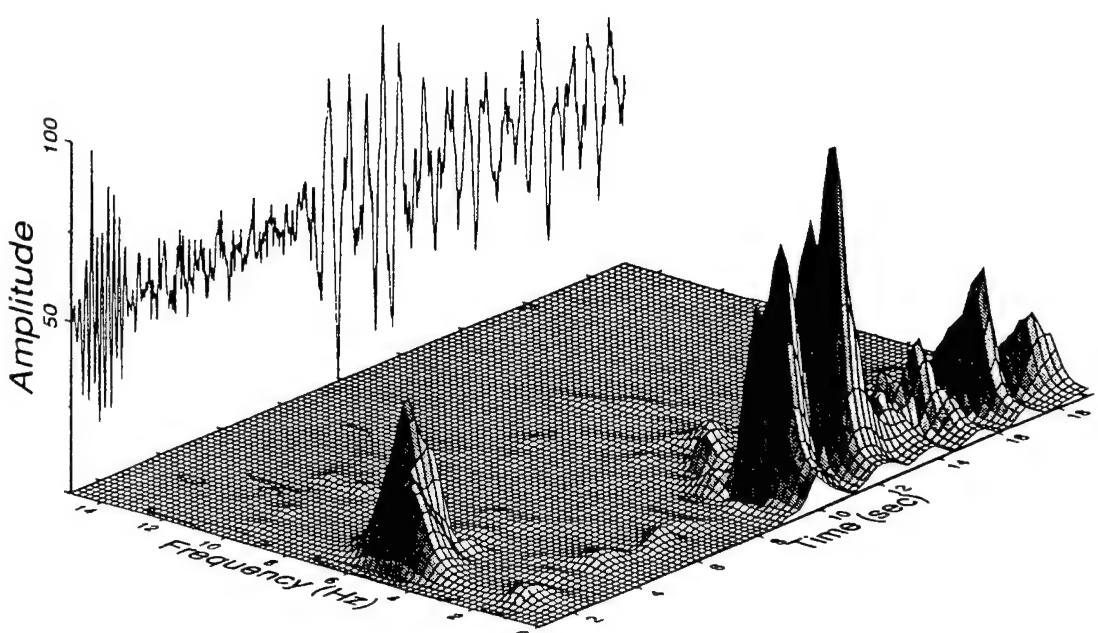


**d)**

**Oct._13th_1994_Fch**

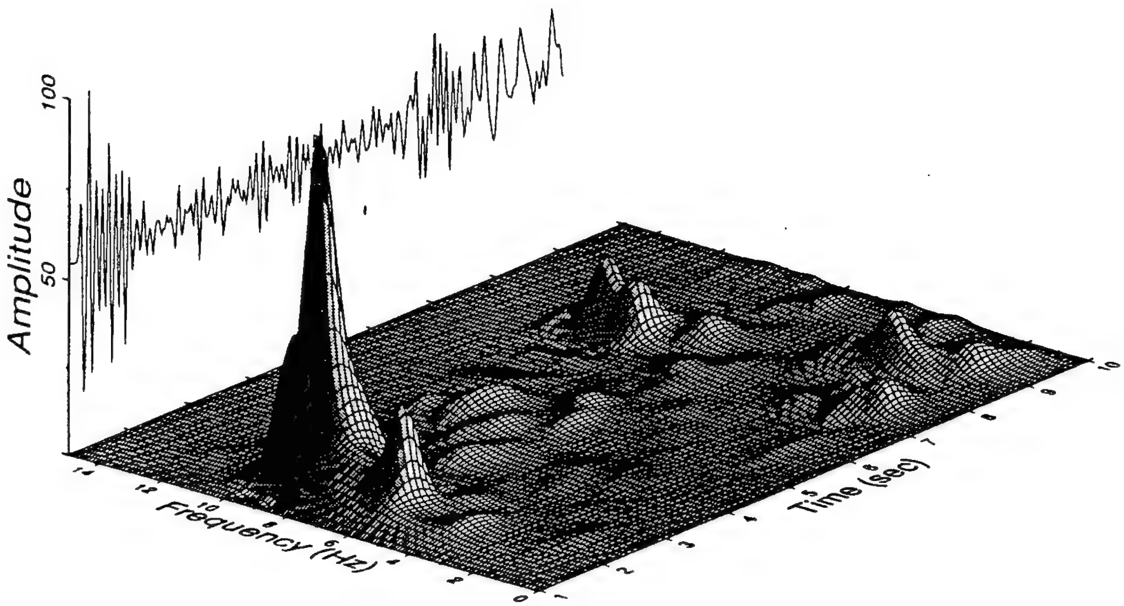



**Oct._13th_1994_Pch**



**a)**

**Jan._9th_1996_Fch**




**Jan._9th_1996_Pch**

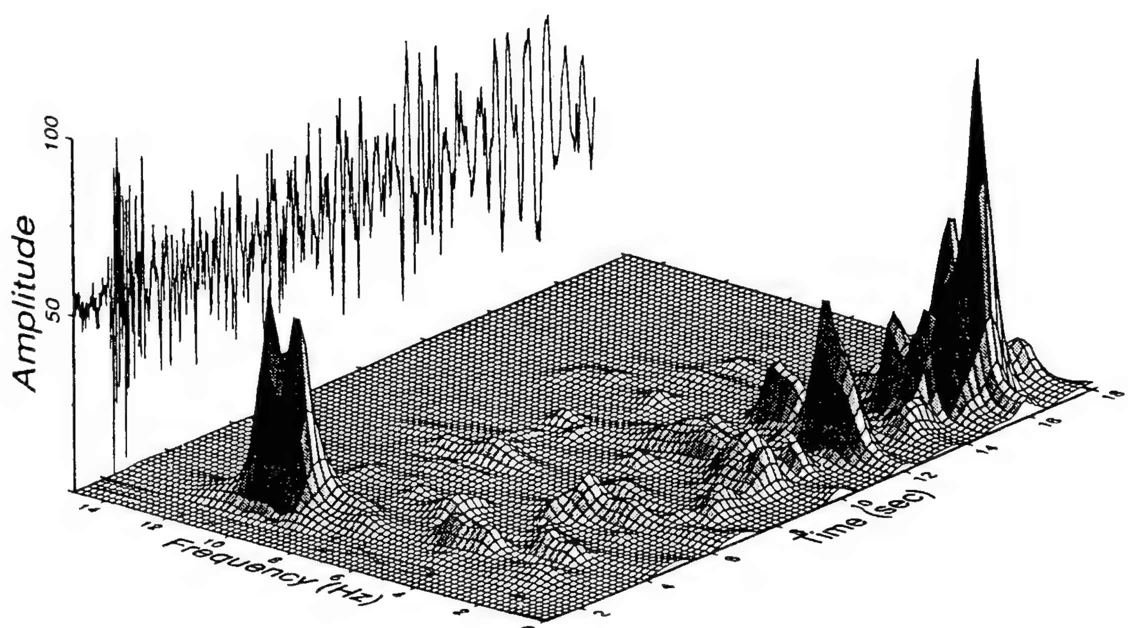
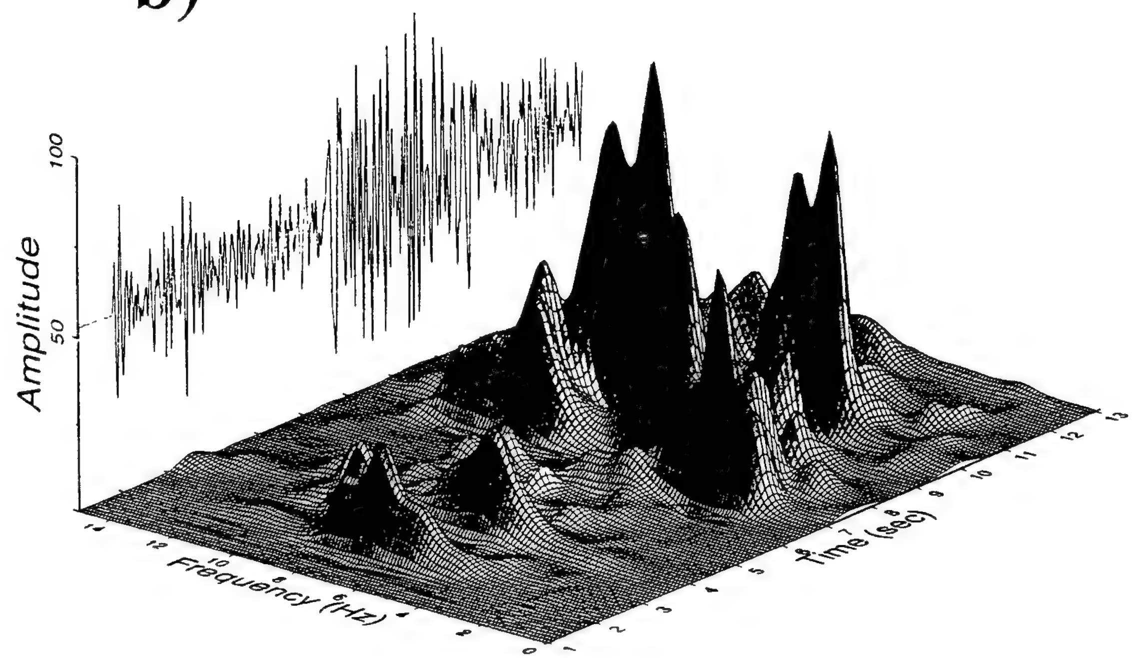


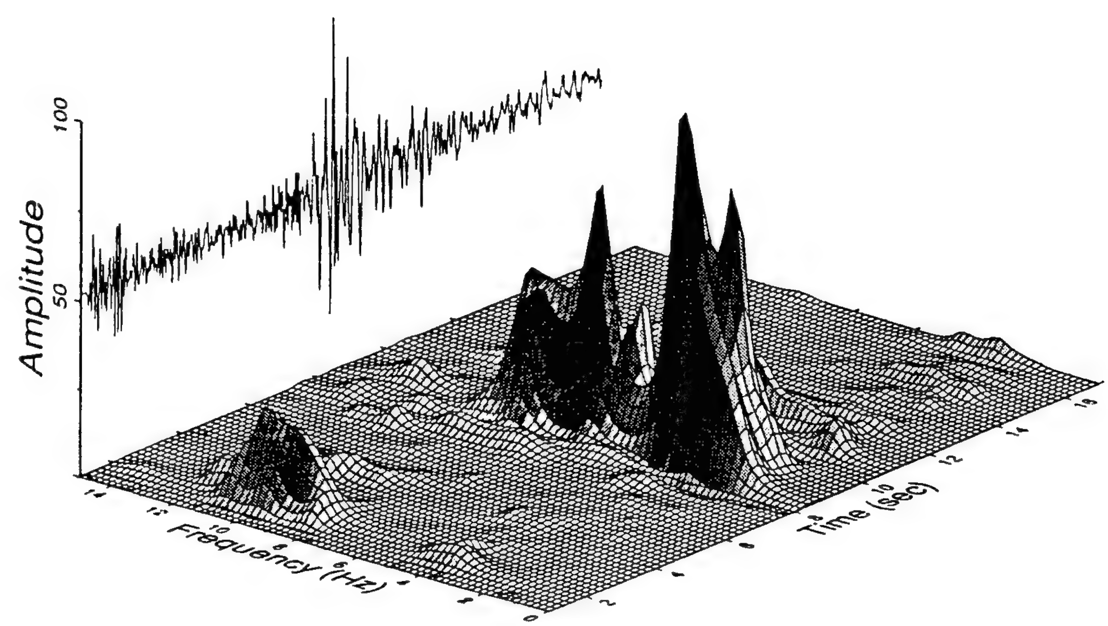

Figure 10. Spectrograms for four earthquakes recorded at stations FCH and PCH. (a) event 01/09/96, (b) event 03/18/96, (c) event 04/21/96, (d) event 04/29/96.

March_18th_1996_Fch

**b)**

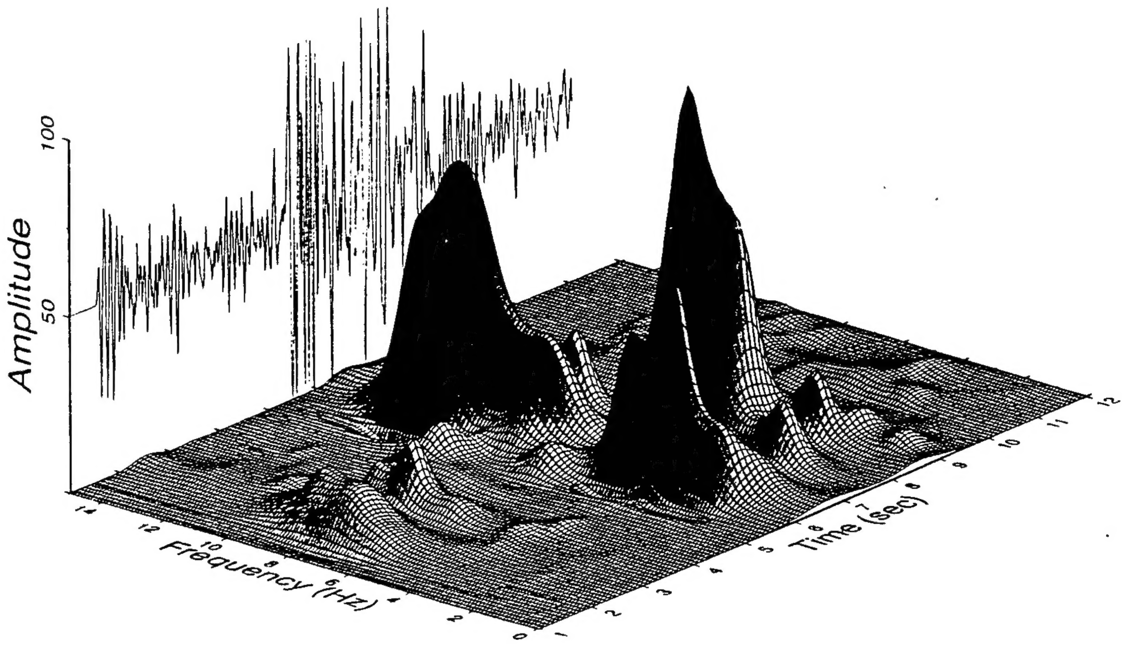



March_18th_1996_Pch

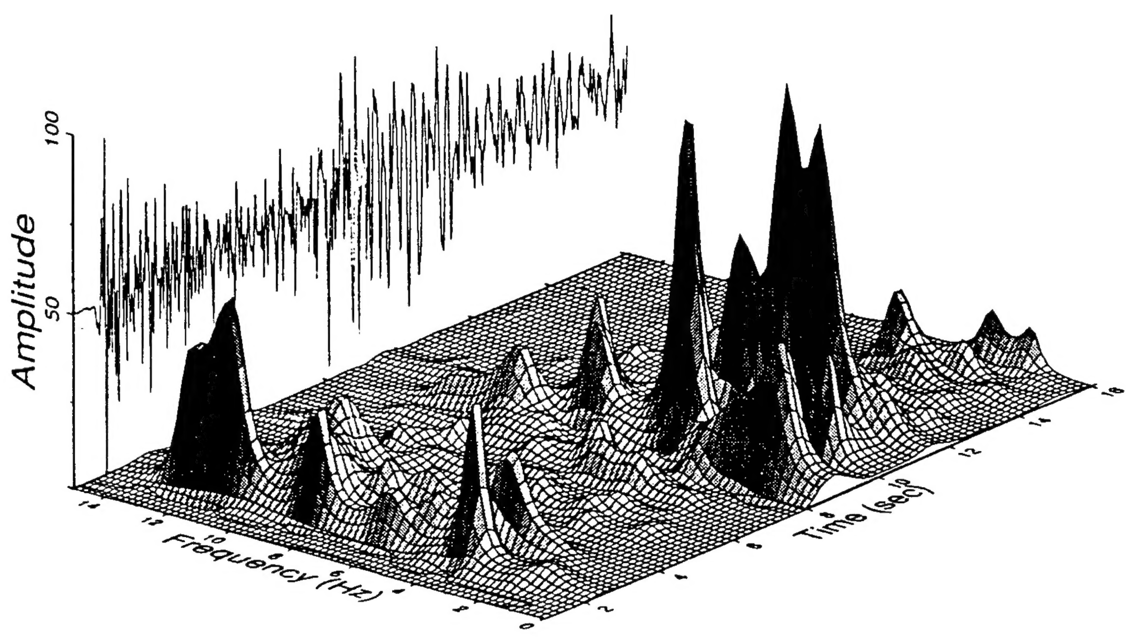


c)

April_21st_1996_Fch

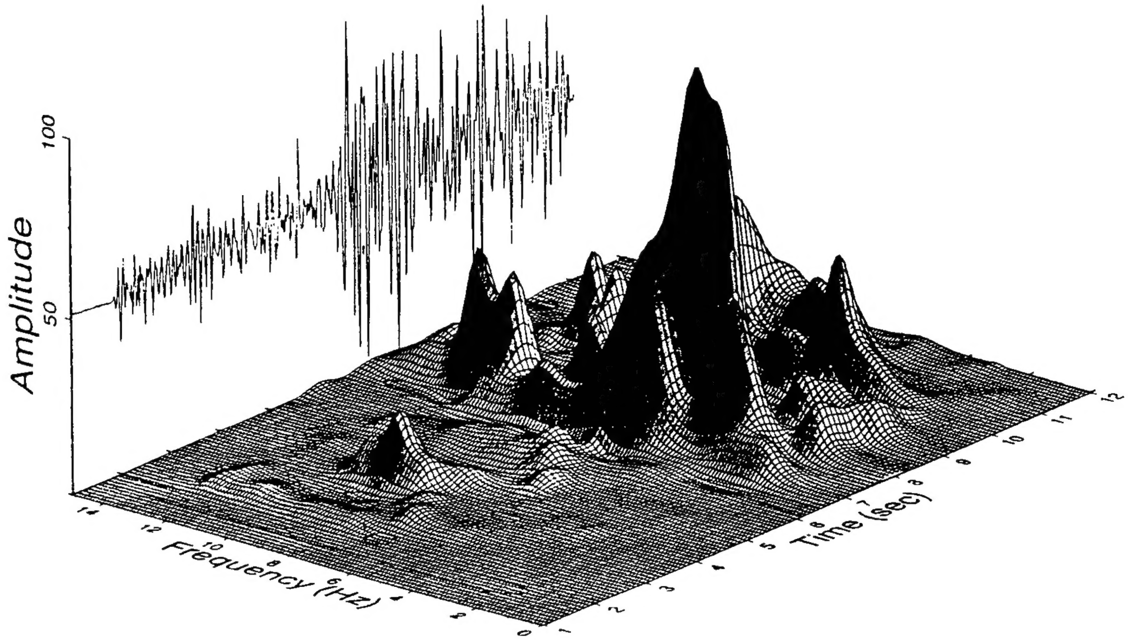



April_21st_1996_Pch

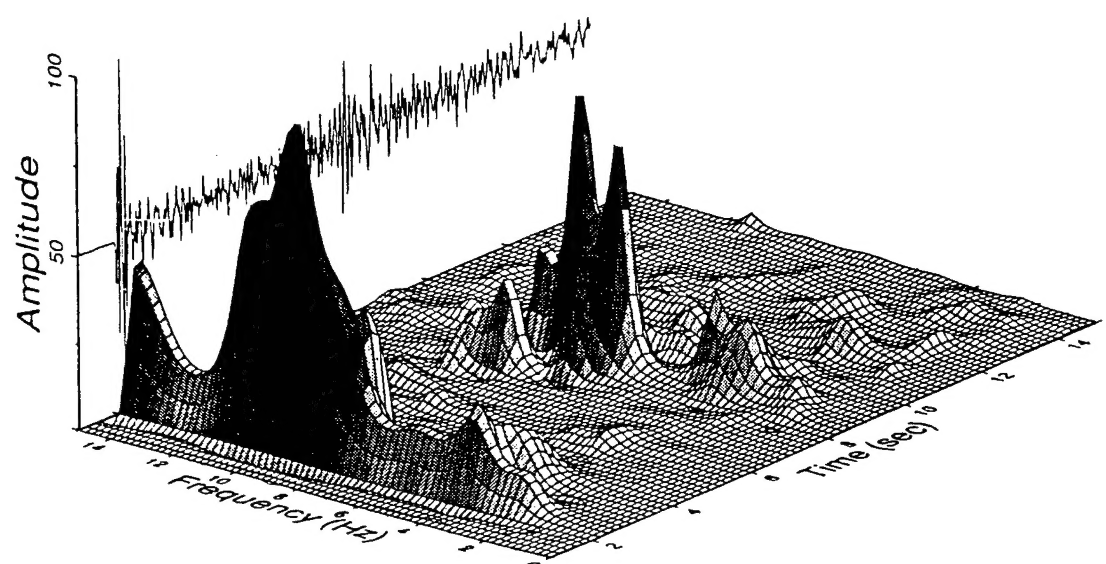


d)

April_29th_1996_Fch




April_29th_1996_Pch



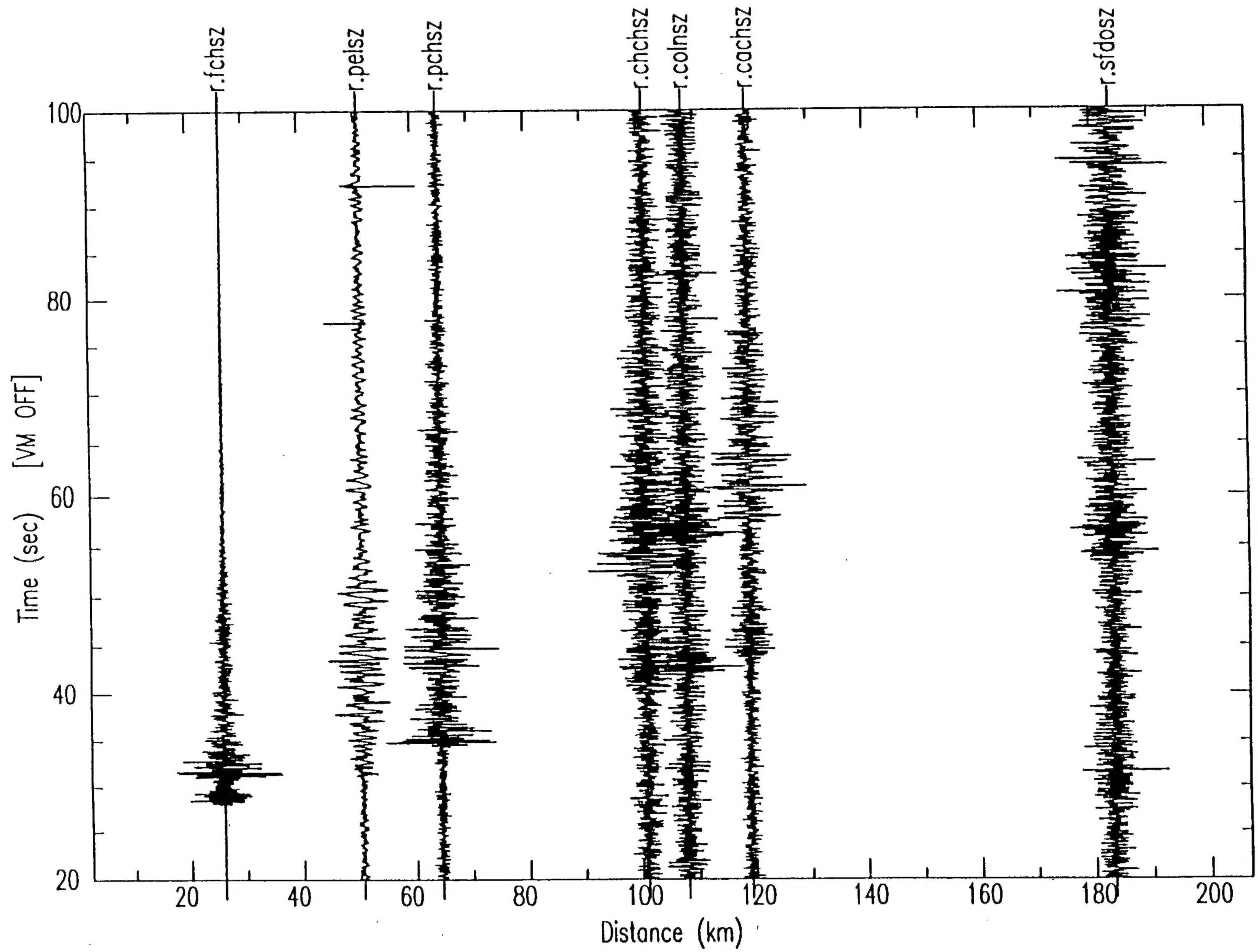
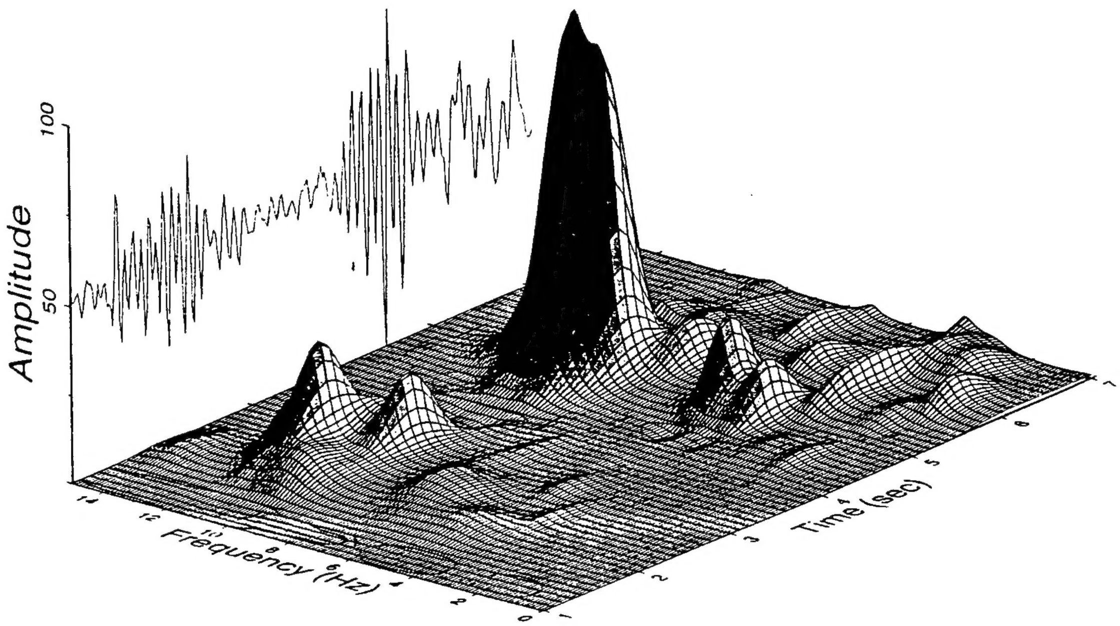



Figure 11. Record section plot for an event on 10/20/94 that locates approximately 18 km east of the active mine Disputada in Chile. The event is small (duration magnitude 3.27) and not well recorded across the network.

Oct._20th_1994_Fch




Oct._20th_1994_Pch

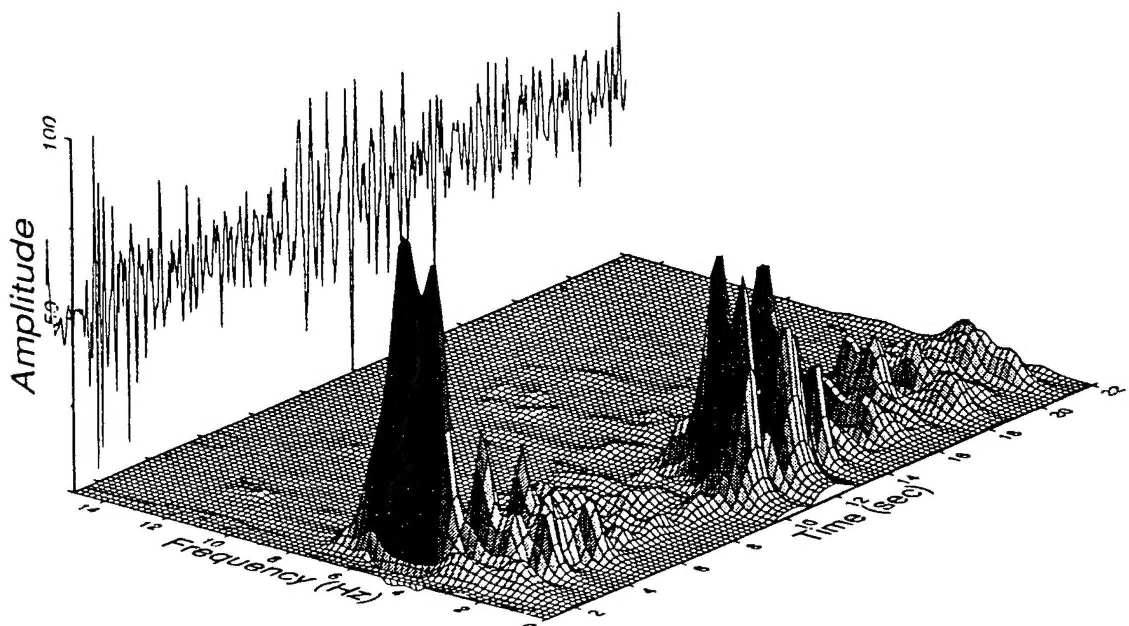



Figure 12. Spectrogram of an event (10/20/94) recorded at stations FCH and PCH.